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ABSTRACT

Research in cognitive science that can be incorporated into the instructional design process is summarized. Instructional design shares many features common to other types of design, but its models do not support the kinds of cognitive activities necessary for successful design. Assumptions about learning provided by the descriptions of cognitive science also represent challenges to current instructional design models. Decisions made about instruction should reflect these assumptions, but this is difficult to achieve unless the designer is aware of the assumptions and the model used to guide decision making supports those assumptions. The necessity of developing new tools and analytical procedures for instructional design is discussed. The tools used to design instruction must reflect the assumptions about learning that are inherent in cognitive science theories. The role of the designer may have to be redefined in the next generation of instructional design to reflect the disciplines' commonalities with knowledge engineering. The development of a sufficient knowledge base related to specific design problems and solutions is also critical. One flowchart and a 61-item list of references are included. (TJH)

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**Reconceptualizing the instructional design process:
Lessons learned from cognitive science**

For more than a decade, researchers have advocated an approach to instructional design that is based in cognitive psychology (Low, 1980; Wildman & Burton, 1981). Nevertheless, significant change in the field has been slow to occur; our conception of the instructional design process has not kept pace with developments in cognitive science. The many published instructional design models prescribe systematic means for making decisions about the content, strategies, and assessment of instruction (see Andrews & Goodson, 1980). The problem is that despite differences in outward appearances, many of these models support underlying assumptions based largely in outmoded theories of learning.

The integration of cognitive theory into instructional design models has been difficult because of the nature of research in cognitive science. In the past twenty years, great progress has been made in describing the knowledge structures and cognitive processes of experts and novices in a variety of domains, but little research validating learning or instructional theories has been undertaken. Many believe that it is now time to generate theories that describe how knowledge structures are acquired (Glaser, 1989a), and instructional designers will have to be involved in the process if the field is to evolve along with its underlying theory base. However, in order to do this, it is necessary to develop new learning and instructional theories from the existing theoretical descriptions provided by cognitive science.

Howard Gardner (1985) defines cognitive science "... as a contemporary, empirically based effort to answer long-standing epistemological questions -- particularly those concerned with the nature of knowledge, its components, its sources, its development, and its deployment" (p. 6). The view of the mind which dominates most research in cognitive science describes thought as symbolic computation (information processing) based on the analogy of the computer (Atkinson & Shiffrin, 1968; Newell & Simon, 1976; Pylyshyn, 1980). Cognitive science investigates processes, not products; thoughts, not behaviors. Instruction based in principles of cognitive science, therefore, must provide the learner with the required knowledge and help the learner to activate appropriate cognitive processes in order to store the knowledge so that it can be retrieved for later use.

The relationship between the instructional design process and the related theoretical fields now being influenced by cognitive science is depicted in Figure 1. Research in cognitive science has been able to describe the knowledge structures and cognitive processes of an individual at both points A (the novice) and B (the expert). Glaser (1989b) suggests that we can now begin to describe the changes in knowledge structures and cognitive processes which occur as an individual progresses from point A to point B. If these changes can be specified as a learning theory, then a related instructional theory can be developed which will assist the individual in learning. Cognitive science has reached the point of maturity where learning and instructional theories are being proposed (e. g. Bereiter, 1991), and the field of instructional design should be participating in these endeavors.

Insert Figure 1 about here

Further, the instructional design process itself can be examined from the perspective of cognitive science, providing a description of how instructional designers solve design problems, how their assumptions about learning affect the decisions they make, and how models and tools can be designed to better facilitate an instructional design process that reflects the research base of cognitive science. Even if instructional designers do not participate in the development of new learning and instructional theories, examination and revision of the current approach to instructional design, given the new perspectives provided by cognitive science, is necessary. The remainder of this paper focuses on some of these issues.

Instructional design from the perspective of cognitive science

Instructional design is frequently characterized as a systematic process for analyzing and specifying solutions to instructional problems. The systematic models used by instructional designers have been influenced by general systems theory and the method of inquiry commonly referred to as the "scientific" method. But design is not a science (not yet, anyway). The goals of design inquiry and scientific inquiry differ significantly. The goal of science is to produce knowledge from systematic observation and analysis, a largely inductive process. The goal of

design is to produce an artifact which meets a set of requirements, a largely deductive process (Coyne, Rosenman, Radford, Balachandran, & Gero, 1990).

The characterization of the instructional design process as a "scientific", systematic process is a somewhat simplistic view of how scientists actually work (Tripp & Bichelmeyer, 1990). Popper (1972), and more recently Simon (1989), have described scientific inquiry as a problem-solving process where goals are established and a continual process of transformation/refinement of the problem is undertaken. From this perspective, design is an "artificial" science (Simon, 1981) where a largely ill-structured problem (initial design requirements) is iteratively refined into subproblems which have well-structured characteristics that can be readily solved. Design then involves processes of search and optimization, where the "best" solution to each subproblem is chosen in order to satisfy the greatest number of specified requirements.

Design inquiry as a problem-solving process forms the basis of methods developed by architectural designers (Alexander, 1964), who advocate a recursive, three-phase model consisting of analysis, synthesis and evaluation activities. Observations of designers in various domains have confirmed such activities (Akin, 1979; Eastman, 1972; Nelson, 1988). The major characteristic of design inquiry is a cycle of cognitive activity where all facets of the problem are considered numerous times. Complete analysis is not necessary before synthesis can begin, and so on. Each time a new issue is attended to, a new solution goal is developed, decisions are made with respect to the goal, and the problem is reconsidered in light of that evaluation. It would appear that the design process is circular or spiral (Banathy, 1988), and not linear, as depicted in many instructional design models.

Successful design activity is directly related to the designer's experience and knowledge. Environmental cues related to the nature or constraints of the problem can often evoke a precompiled solution from the designer's memory very early in the process, indicating the influence which the designer's knowledge has on the design process (Nelson, 1988). Knowledge structures stored in the designer's memory automate and control the process of problem decomposition, allowing the designer to focus on the details of the problem rather than controlling the process (Jeffries, Turner, Polson, & Atwood, 1981). Specific knowledge about the design process also enables the designer to solve sub-problems in prototypical ways based on previous experience, controlled by metacognitive strategies that determine which subproblem needs current

attention, how much attention is needed, and when the subproblem is solved. Metacognitive strategies and prior experience may also influence the choice of the initial design model, and the depth to which analysis, synthesis, and evaluation should proceed for a particular problem, including pragmatic decisions represented in a "layers of necessity" model of instructional design (Tessmer & Wedman, 1990).

Knowledge, then, is the key to instructional design. The knowledge available to instructional designers, either individual knowledge stored in the designer's memory or other forms of knowledge embodied in the models and tools used for design, will influence the kinds of designs they create. In order to utilize the findings of cognitive science to design instruction, it is essential that designers use assumptions about learning derived from cognitive science as the basis for making decisions about instruction, and that appropriate knowledge-based tools for instructional design be available to aid the analysis, synthesis, and evaluation activities common to design activities. The following sections of this paper explore these two areas in more detail.

New assumptions about learning

Knowledge about learning is essential for instructional designers, providing support for decisions about instruction, and the basis for the models used to design instruction. Glaser (1989b) has summarized several areas of research where well-defined descriptions of cognition that address Gardner's concerns for the nature of knowledge, its components, its sources and its deployment have been established. Those areas include: knowledge organization and structure, problem solving, automaticity to reduce attentional demands, and metacognitive skills. These areas provide more comprehensive information for deriving instructional objectives, designing learning conditions, and assessing acquired knowledge and skills than is available in current instructional design models. The following paragraphs briefly describe the major findings in these areas of research, along with implications for instructional design.

Knowledge Organization and Structure

The processes by which knowledge is acquired, organized and retrieved from long-term memory have been the focus of a great deal of research in cognitive science. Numerous models of memory organization have also been proposed, including semantic networks (Collins and Loftus, 1975), propositional networks (Anderson, 1983), and rule-based productions (Anderson, 1987).

Studies of exceptional memorial processes have demonstrated distinct differences between encoding and retrieval skills of novices and experts (Ericsson and Staszewski, 1989). As competence develops, knowledge structures become more interconnected, thereby increasing retrieval speed.

Objectives for instruction should reflect the structure, organization and retrieval of information from long-term memory. This does not mean isolated facts, but rather a new relationship between subject matter and student where knowledge is the focus of comprehensive instructional activities. If there is a specific organization that constitutes knowledge in a given domain, then that structure ought to be provided to the learner. If there are encoding or retrieval strategies that can aid the acquisition of a particular component of a knowledge structure, then strategies ought to be provided to the learner.

Problem Solving

Much research on expert-novice differences in problem solving has shown that an expert tends to go beyond the surface aspects of a problem to a deeper understanding which allows the expert to "see" a different problem than the novice sees (Chi, Glaser, & Farr, 1988). Such depth of problem representation might be the result of differences in syntactic and semantic understandings of problems (Resnick, 1982). In this sense, novices may be focusing attention on syntactic concerns without completely understanding the semantics of the operations. This factor is revealed in research examining novices' retrieval processes, which tend to focus on syntactic or superficial aspects rather than the logical chunks that are utilized by experts within the problem domain (Magliaro & Burton, 1988; McKeithen, Reitman, Rueter, and Hirtle, 1981).

Experts also solve problems by pursuing goals that are closely tied to solution procedures. The purpose of carrying out a procedure is defined throughout the process, thereby eliminating unnecessary solution steps. Anderson (1987) has developed a theory for the acquisition of procedures which has been operationalized in the context of computer tutors. He is quite clear about how knowledge progresses from declarative to procedural structures, and is eventually compiled into automatic procedures.

Problem solving can be improved in a variety of ways, including tasks in verbal and graphic situations which facilitate the learner's recognition and perception of patterns of information in a problem. It is also important to provide instruction in a problem-solving context so that encoding

and retrieval are increased because the context of study matches the context of performance. Worked examples and other goal-free problems can help to reduce cognitive load and facilitate learning (Sweller, 1989). Above all, explicit communication of the solution process and the goal structures underlying the solution are necessary. This can best be achieved through successive approximation of the target skill (Anderson, Boyle, Farrell, & Reiser, 1987).

Automaticity to Reduce Attentional Demands

Experts do not require the attentional resources that novices require because they have automated some of the problem-solving procedures within their domain of expertise. This allows more conscious processing capacity to be devoted to higher levels of processing, and reduces interference with low level subprocesses. Much research indicates that the only way to achieve automaticity is through considerable practice, which should be designed to help the learner identify the aspects of the task that require the various component skills, and the interrelationships between the component skills and the larger task goal (Glaser, 1989b).

Metacognitive Skills

Experts utilize metacognitive knowledge which helps them approach new problems and monitor performance in ways that novices do not employ. In other words, the application of procedural knowledge is enhanced when its suitability for the particular situation is monitored. From the perspective of cognitive science, a major focus of instructional design should be the learning strategies which are appropriate for the content and learners involved in a particular situation. The overall goal of instruction which supports self-regulatory skills is to promote the utilization of effective strategies by learners in various situations. "Strategy learning improves content learning, and vis versa" (West, Farmer & Wolff, 1990; p. 18), therefore, an emphasis on designing instruction to support the learners in organizing, structuring, and relating knowledge should become the major component of instructional design models. Much of the support for this notion comes from research on reciprocal teaching (Brown & Campione, 1977; Palinscar & Brown, 1984), which is based on the idea of metacognition (Brown, 1975; Flavell, 1985).

Incorporating New Assumptions About Learning

Instructional designers have recognized the need to incorporate cognitive theories of learning into instruction, and many of the current instructional models have been modified to include principles of cognitive learning theories (See Reigeluth, 1983). Theorists continue to revise and

expand models of instructional design as more knowledge becomes available. For example, Tessmer, Wilson, and Driscoll (1990) have proposed a new model of concept teaching which differs significantly from previous ideas about concept acquisition, suggesting that concepts are actually complex networks or schema that require a variety of instructional strategies. Gagne' and Merrill (1990) have proposed higher levels of learning outcomes which would incorporate multiple objectives in the form of "enterprise schema" which embody the more comprehensive goals learners bring to the instructional setting. Such a modification reflects the recommendations about instruction made by researchers in cognitive science (Anderson, Boyle, Farrell, & Reiser, 1987).

Gagne's theory (Gagne' 1985; Gagne' & Briggs, 1979; Gagne', Briggs, & Wager, 1989) has also undergone significant modifications during the last decade, with increasing emphasis on information processing descriptions of learning provided by cognitive science. However, the nine "events of instruction" (Gagne', Briggs, & Wager, 1989) may still require further refinements in order to be more applicable for instruction. Orey, Okey, Jones, and Stanley (1991) have described how the nine events need to evolve in order to account for more recent developments within the field of cognitive science.

The model of the intelligent tutoring system is also an excellent example for instructional designers to emulate (Orey & Nelson, 1990). According to the model, instruction should ideally focus on strategies which help learners to generate internal representations of the content, rather than simply subsuming the content through memorization. The emphasis of instruction is solving problems, not remembering disconnected facts. Assessment of learning is ongoing through comparisons between the knowledge organization of the expert and the learner at various points during the instructional process. Adaptive strategies are used to modify instructional procedures when the diagnostic process identifies errors.

Problems to be reconciled in current assumptions about learning

While much of the research in cognitive science can be integrated into current models of instructional design, some of the more recent advances that have been proposed from a constructivist view of learning are more difficult to incorporate (e.g., Brown, Collins, & Duguid, 1989). The constructivist orientation differs significantly from the mainstream of cognitive science. Learning is viewed as a constructive process in which the learner builds a uniquely

personal knowledge base derived from experiences in various situations. Knowledge is constructed through a sharing of multiple perspectives on a particular topic.

Alba and Hasher (1983) describe four principles of schema theory, including selection, abstraction, interpretation, and integration, that form the basis of constructivist descriptions of learning. These processes are present in various learning situations, and much of the research in this area is based on the notion of schematic change. If one can understand how schemata are changed or learned, then there are direct implications for how to cause these changes to occur. The problem is that these theories provide little functional explanation of how schema are established, modified, or integrated, and therefore instructional prescriptions are difficult to formulate.

Despite the lack of specificity in constructivist theories, instructional design can still benefit from an examination of these alternative approaches to learning (Bednar, Cunningham, Duffy, & Perry, in press). For example, it is well established that context can have a powerful effect on learning (Heath, 1983). Whenever possible, instruction should be situated in real-world contexts that are rich in possibilities for individual exploration (Brown, Collins, & Duguid, 1989). The focus of instructional design from this perspective should be the development of authentic tasks and learning environments, along with assessment procedures which can determine how the learner's thinking processes have been changed.

New tools for instructional design

Design models which support the cognitive processes involved in design inquiry, along with appropriate assumptions about learning, need to be developed for instructional design if we are to take advantage of the recent findings of cognitive science. Although some evolution in our approach to instructional design is taking place (Merrill, Li, & Jones, 1990), much more work must still be done . In this section, tentative suggestions are made for the modification of instructional design models and the tools used to design instruction.

A new approach to the instructional design process

As mentioned earlier, the cognitive requirements of instructional design differ greatly from many of the "systematic" models commonly advocated in the literature. We suspect that many people, when first exposed to an instructional design model, react as we did when attempting to employ a "systematic" model for instructional design. That is, the process is represented as a

linear flowchart, occasionally with feedback loops for formative evaluation, which seems to imply that one should proceed through the process in a sequential fashion, never considering instructional strategies before objectives are sequenced, never selecting media before strategies are specified, etc. Of course, with experience we realized that the instructional design process must be flexible; that it is common to think about the problem through iterations of the whole process and not in a sequential manner. Why can't that characteristic be communicated in the descriptions of the instructional design process found in many texts?

The design process would also be streamlined by the adoption of rapid prototyping strategies typically used in computer software development (Tripp & Bichelmeyer, 1990). This kind of approach supports the cognitive processes of design described earlier, where the designer is involved in iterations of a analyze/synthesize/evaluate cycle. Rapid prototyping allows the designer to see the results of decisions much more quickly, and encourages a process in which design alternatives are tested and modified through interaction with the intended learners.

Like Striebel (1989), we have also been thoroughly frustrated when trying to employ conventional instructional design methods to design contextualized or "discovery-based" instruction. If everyone has unique knowledge of a domain, as surmised by constructivist theories, how can appropriate content be identified? How can objectives be specified and sequenced when the object of the learning activities is for an individual to explore a learning environment? How can assessment of learning be made in such settings? Existing design models do not provide answers to these questions, nor do they guide decision making in such situations. We agree with Bednar, Cunningham, Duffy, and Perry (in press) that considerable effort needs to be directed toward the development of instructional design models which support constructivist principles.

New tools and design techniques

If knowledge is the key to learning, as well as to the process of instructional design, then instructional design must find methods to map information from the real world into symbols and operations that are stored in the learner's mind. In order to do so, more comprehensive analysis procedures are necessary to clearly specify characteristics of competent performance. Cognitive task analysis is more thorough than other analytical procedures commonly used by instructional designers, often relying on analysis of think-aloud protocols obtained while an expert solves a

problem. Cognitive task analysis can be used to examine the performance of domain experts in solving problems, focusing on how their knowledge is organized, and how they use the knowledge to solve problems (Glaser, 1989b; Means, Roth, Schlager, & Mumaw, 1989). Comparisons can be made with a similar analysis of the learners, and instruction can then be devised so that learners' current knowledge can be augmented and restructured to more closely resemble the organization and problem-solving strategies of experts.

Numerous other techniques which differ from those employed by instructional designers could also be employed (Nelson, 1989). While it may be argued that such techniques are unwarranted for instructional design, there is still a significant lack of techniques derived from cognitive science that are employed to help design instruction. If we expect to successfully integrate cognitive theories into instructional design, it will be necessary to adapt design and development techniques from cognitive science for our purposes. For example, techniques for instructional analysis and learning assessment should come from the methods used in cognitive science, such as secondary tasks and protocol analysis, but little use of these techniques appears in the instructional design literature (Smith, 1988).

Traditional methods for content and instructional analysis will also need to be altered to design effective contextualized instruction based in constructivist principles of learning. Analytical activities should focus on how experts use knowledge in the context of real-world problems, requiring a much more detailed environmental analysis such as that proposed by Tessmer (1990). Detailed descriptions of deficiencies in the learners' current knowledge may not be necessary, since each learner will bring a unique perspective to the instructional situation. Performance objectives may not be necessary from this perspective, either. The search for authentic tasks becomes the major concern of the designer, and characteristics of the instructional environment can have great impact on the success of instructional activities.

Several tools are currently available which can streamline the knowledge acquisition process necessary for instructional design. The content organization of a domain can be elicited with the use of knowledge mapping techniques (Esque, 1988). Computerized tools are available for implementing these techniques to extract knowledge directly from an expert (Ingram, 1989; Wood & Ford, 1990). Such tools are useful for the development of hypertext databases, and may also be appropriate for other applications. Similar tools exist to elicit procedural definitions or production

rules. One particular application uses a learning-by-example paradigm to derive production rules based on object definitions supplied by the user (Neuron Data, 1991). More common applications such as word processors and databases are also helpful in automating the instructional development process (Cantor, 1988).

Hopefully, the great interest in automating instructional design and development (Wilson & Jonassen, 1991) will result in tools that may eventually be incorporated into intelligent systems for instructional design. Such tools would make the design and development process more efficient, allowing the designer to focus on controlling and managing the process at higher levels of the process. The cognitive requirements for design need to be considered when developing tools for instructional design. These tools must support the kinds of cognitive activities designers typically undertake, and not fragment the process into discrete but unrelated activities.

Summary: A new knowledge base for instructional design

This paper has summarized research in cognitive science which can be incorporated into the instructional design process. Instructional design shares many features common to other types of design, but our models do not support the kinds of cognitive activities which are necessary for successful design. Assumptions about learning provided by the descriptions of cognitive science also represent challenges to current instructional design models. Decisions made about instruction should reflect these assumptions, but that is difficult to achieve unless the designer is aware of the assumptions and the model used to guide decision making supports those assumptions. Finally, the necessity of developing new tools and analytical procedures for instructional design was discussed. The tools we use to design instruction must also reflect the assumptions about learning that are inherent in cognitive science theories.

The role of designer may also have to be redefined in the next generation of instructional design. We believe that instructional design has much in common with knowledge engineering, and that in order to incorporate cognitive science principles into instructional design, we have to think of ourselves as knowledge engineers. The potential exists for the field of instructional technology to take a leadership role in the advancement of cognitive science. After all, one of the best testbeds for a learning theory is an instructional application of the theory. In order to achieve

this role, we need to reflect the appropriate assumptions about learning in our instructional design models.

Knowledge about the design process can also be used to better train new instructional designers. The development of a sufficient knowledge base related to specific design problems and solutions is critical. The design process is much less intimidating if a novice designer can say "Ah, I've seen that kind of problem before." In order to make appropriate decisions about instruction, the "new breed" of instructional designers must be trained in cognitive science, computer science, and instructional technology, not just instructional technology. In this way, the next generation of instructional systems can be derived from an enlightened viewpoint, and not just generated capriciously.

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Figure 1.
Relationships between instructional design and related theoretical fields.